Forest Ecology and Management 432 (2019) 17–29

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

# Carbon dynamics and land use carbon footprints in mangrove-converted aquaculture: The case of the Mahakam Delta, Indonesia

Virni Budi Arifanti[a,b,*], J. Boone Kauffman[a], Deddy Hadriyanto[c], Daniel Murdiyarso[d,e], Rita Diana[c]

[a] Department of Fisheries and Wildlife, Oregon State University, 104 Nash Hall, Corvallis, OR 97331, USA
[b] Center for Research and Development of Social, Economy, Policy and Climate Change (P3SEKPI), Ministry of Environment and Forestry of the Republic of Indonesia, Jl. Gunung Batu No. 5, Bogor 16118, Indonesia[1]
[c] Faculty of Forestry, Mulawarman University, Kampus Gunung Kelua, Jl. Panajam, Samarinda 75123, Kalimantan Timur, Indonesia
[d] Center for International Forestry Research (CIFOR), Jl. CIFOR Situgede, Bogor 16115, Indonesia
[e] Department of Geophysics and Meteorology, Bogor Agricultural University, Kampus Darmaga, Bogor 16680, Indonesia

ARTICLE INFO

*Keywords:*
Carbon dynamics
Ecosystem carbon stocks
$CO_2$ emissions
Emission factor
Mangroves
Aquaculture
Carbon footprint
Climate change

ABSTRACT

Mangroves provide a number of important ecosystem services to humanity but their persistence is threatened from deforestation, conversion, and climate change. The Mahakam Delta was once among the largest mangrove forests in Southeast Asia comprising 2% of Indonesia's total mangroves. Currently, about 62% of this extensive mangrove in the Mahakam Delta has been lost mainly due to conversion into aquaculture. To understand the impacts of mangrove conversion on carbon losses and therefore their values in climate change mitigation, we sampled 10 intact mangroves and 10 abandoned shrimp ponds to quantify: (1) the total ecosystem carbon stocks; (2) potential $CO_2$ emissions arising from mangrove conversion to shrimp ponds; and (3) the land use carbon footprints of shrimp production. The mean ecosystem carbon stocks in shrimp ponds ($499 \pm 56\,\mathrm{Mg\,C\,ha^{-1}}$) was less than half of the relatively intact mangroves ($1023 \pm 87\,\mathrm{Mg\,C\,ha^{-1}}$). This equates to a potential annual emission factor over 16 years following mangrove conversion of $120\,\mathrm{Mg\,CO_2e\,ha^{-1}\,yr^{-1}}$, which is similar with the total carbon loss from land conversion in freshwater tropical peat swamp forests. Inclusion of C losses from land use/cover change in a life cycle analysis (i.e., the land use carbon footprint) resulted in an estimated 2250 kg $CO_{2\text{-}e}$ emitted for every kg of shrimp produced in mangrove-converted ponds. Conversion of mangroves to shrimp ponds in the Mahakam Delta resulted in a carbon loss equivalent to 226 years of soil carbon accumulation in natural mangroves. Conservation of mangroves are of great value for inclusion in climate change mitigation strategies because of their large carbon stocks, the large carbon emissions generated from land use, and the potentially long period of time required to recover carbon stocks following abandonment.

## 1. Introduction

Mangrove ecosystems are wetlands consisting of woody vegetation that occur in intertidal marine and brackish environments (Giesen et al., 2007). They are distributed along coasts in tropical and subtropical regions between approximately 30°N and 30°S latitude (Giri et al., 2010). Indonesia has 29,000–31,894 $\mathrm{km}^2$ of mangroves which is more than any other country on earth (i.e. 21–23% of the global total; FAO, 2007; Giri et al., 2010; Spalding et al., 2010).

Mangrove ecosystems provide many valuable ecological functions and services such as fish habitat (Alongi, 2009; Nagelkerken et al., 2008), timber, thatch and fuels (Blasco et al., 1996), habitat for endemic animals and organisms (Nagelkerken et al, 2008) and they provide coastal protection from extreme events such as tsunamis and hurricanes (Alongi, 2008; Giri et al., 2008, 2010). They also store and sequester relatively large quantities of carbon (Donato et al., 2011; Mitsch et al., 2012; Murdiyarso et al., 2015; Kauffman et al., 2017).

Farmed shrimp is now the largest seafood commodity accounting for 15% of the total value of all fishery products traded internationally in 2012 (FAO, 2014). A global export market for shrimp has led to large areas of mangrove loss (Bosma et al., 2012; Ilman et al., 2011; Pendleton et al., 2012). Aquaculture pond establishment has been the

---

[*] Corresponding author at: Center for Research and Development of Social, Economy, Policy and Climate Change (P3SEKPI), Ministry of Environment and Forestry of the Republic of Indonesia, Jl. Gunung Batu No. 5, Bogor 16118, Indonesia

*E-mail addresses:* vbudia@yahoo.com, Virni.Arifanti@oregonstate.edu (V.B. Arifanti).

[1] Permanent address.

https://doi.org/10.1016/j.foreco.2018.08.047
Received 29 January 2018; Received in revised form 16 August 2018; Accepted 27 August 2018

main cause of mangrove deforestation in Asia (FAO, 2007; Giri et al., 2008) followed by conversion to agriculture (oil palm plantations, pasture, etc.), urban development, infrastructure and tourism (Duke et al., 2007; FAO, 2007; Giri et al., 2008).

Land use change in mangrove ecosystems generates significant $CO_2$ emissions (Kauffman et al., 2017; Pendleton et al., 2012; Werf et al., 2010). Between 1980 and 2005 Indonesia lost about 30% of its mangrove forests which is equivalent to an annual deforestation rate of 1.24% or an estimate of 0.19 Pg $CO_{2e}$ $yr^{-1}$ (FAO, 2007; Murdiyarso et al., 2015).

While rates of land conversion of mangroves are high, very few studies have analyzed the carbon footprint from shrimp production that includes the emissions arising from land use/cover change (Järviö et al., 2017; Kauffman et al., 2017). This loss, when included in life cycle analyses, is termed the land use carbon footprint and is defined as the quantity of greenhouse gases produced from the land conversion that is required to produce any given commodity (Kauffman et al., 2017). The objectives of this study were to quantify the total carbon stocks in mangroves and abandoned shrimp ponds, the potential carbon emissions arising from mangrove conversion, and the estimated land use carbon footprint of shrimp produced in the Mahakam Delta, Indonesia.

We hypothesized that: (1) the ecosystem C stocks in intact mangroves are significantly higher than in shrimp ponds; (2) mangrove conversion to shrimp ponds will generate substantial carbon emissions to the atmosphere because of significant losses (oxidation) of the aboveground pools and soil carbon; and (3) potential $CO_2$ emissions arising from mangrove conversion to shrimp ponds result in a very high ecosystem carbon footprint from aquaculture ponds.

## 2. Materials and methods

### 2.1. Study area

The Mahakam Delta is a deltaic plain on the Eastern coast of Kalimantan (Borneo) Island, Indonesia. The Mahakam Basin is approximately 75,000 $km^2$ in area. The Mahakam River 900 km in length (Sassi et al., 2011; Storms et al., 2005) and is located between 0°18′ and 0°54′ South latitude, and 117°18′ and 117°36′ East longitude (Rahman et al., 2013). The delta was developed in the late-Holocene during the past 5000 years and has a distinct network of fluvial and tidal channels forming a lobate, fan shaped delta (Fig. 1; Storms et al., 2005).

Before 1950, the natural mangrove vegetation of the Mahakam Delta was relatively undisturbed. It was dominated by Nypa palm (*Nypa fruticans;* 50% of the delta area), freshwater tidal forests (17%) and broadleaved mangroves at the lowest reaches (33%) (van Zwieten et al., 2006). The development of aquaculture ponds was largely concentrated in the broadleaved mangroves until recently (Bourgeois et al., 2002). Rahman et al. (2013) estimated that 21,000 ha mangroves in the Mahakam Delta had been converted to shrimp ponds between 2000 and 2011. Mangrove deforestation in the Mahakam Delta from 1994 to 2015 totaled 59,480 ha, with about 36,820 ha of mangroves remaining in 2015 (Aslan, 2017). They reported that with a deforestation rate of 4.48% $year^{-1}$, about 62% of mangroves had been lost during this 21 year period.

The shrimp ponds in the Mahakam Delta are largely low input/low production operations that depend upon tides to fill and drain ponds. During the first year of pond establishment these ponds produce around 100–300 kg of shrimp $ha^{-1}$ $yr^{-1}$ (Bosma et al., 2012). After 5 years, the average shrimp production in the ponds in the Mahakam Delta significantly decreases to 45 kg $ha^{-1}$ $yr^{-1}$ (Noryadi et al., 2006). Decreased aquaculture productivity, sea level rise, diseases, and harvest failures ultimately results in abandonment of ponds (Bosma et al., 2012).

We quantified ecosystem carbon stocks in ten mangrove communities and ten abandoned shrimp ponds formed in mangroves across the Mahakam Delta (Fig. 1). The mangrove communities and abandoned shrimp ponds were polyhaline and mesohaline estuarine ecosystems (Mitsch and Gosselink, 2007) with soil pore salinity ranging from 13 to 25 ppt.

### 2.2. Field sampling and data analysis

Field measurements closely follow methods outlined in Kauffman and Donato (2012). Carbon stock measurements were conducted by establishing a linear transect that contained six plots of 7 m radius (0.0154 ha) at each site. Each transect was 125 m in length with plots established every 25 m. The transects were positioned randomly and perpendicular to the marine or river ecotone. We estimated tree biomass by measuring tree diameter at 1.3 m height (diameter at breast height) or 30 cm above the highest prop roots for *Rhizophora* spp. Above and belowground biomass of the trees were estimated using species specific allometric equations (Table A). Standing dead wood and downed wood were measured according to the methods outlined in Kauffman and Donato (2012).

Soil carbon pools were collected at the six plots at each site. We measured the soil depth utilizing an open-face peat auger of 6.4 cm radius around the plot center (Kauffman et al., 2014). The soil C stocks were measured by collecting soil samples at the following depths: 0–15 cm, 15–30 cm, 30–50 cm, 50–100 cm and 100–300 cm (Kauffman and Donato, 2012). At each depth interval, a 5 cm sub-sample was collected for laboratory analysis of bulk density and carbon concentration. Soil porewater salinity and pH were measured at each plot.

Mangrove conversion to shrimp ponds has resulted in soil compaction/collapse, thus resulting in increased bulk density and decreased soil porosity (Batey and McKenzie, 2006; Germer et al., 2010). As such, there would be more soil mass in the top 3 m of soils in the abandoned ponds compared to mangroves. Hence, a more realistic comparison would include differences based upon the equivalent soil mass in mangroves and shrimp ponds rather than volume. Comparisons were based on the same mineral soil mass occurring in the top 3 m of soils in mangroves (Kauffman et al., 1998; Kauffman et al., 2015). Mineral soil mass was calculated through subtraction of the carbon density from the total soil bulk density. Soil C density ($C_d$) was calculated as soil bulk density multiplied by soil C concentration (Warren et al., 2012). The soil C stocks of shrimp ponds were then calculated based on equivalent soil mass of the adjacent mangrove forests. Similar methods had been applied to estimate C losses from conversion to cattle pastures in the Amazon and Mexico (Kauffman et al., 1998, 2015) and is a conservative estimation on carbon loss as it assumes there was no erosional losses from the site (Kauffman et al., 2015).

### 2.3. Ecosystem carbon stocks and potential emissions

The ecosystem carbon stocks were estimated by summing all carbon pools (IPCC, 2006; Eq. B.1). The potential emissions arising from mangrove conversion into abandoned shrimp ponds were calculated by stock-difference method to estimate emissions due to land use change (IPCC, 2006; Kauffman et al., 2015; Eq. B.2).

### 2.4. Land use carbon footprints of shrimp production

We determined the land use carbon footprint of shrimp produced from mangrove conversion in the Mahakam Delta using the approach described by Kauffman et al. (2017) (Eq. B.3). The total ecosystem C loss ($C_{conv}$) is the potential $CO_2$ emissions arising from mangrove conversion to shrimp ponds calculated using stock difference method (IPCC, 2006). $N_2O$ emissions ($eN_2O$) from shrimp production during active use was assumed to be 1.69 g $N_2O$ $kg^{-1}$ of shrimp produced (Hu et al., 2012). The global warming potential (GWP) of $N_2O$ was assumed to be 298 (Myhre et al., 2013). Therefore, the $N_2O$ emissions from shrimp production during active use is equal to 503.6 g $CO_2e$ $kg^{-1}$ of

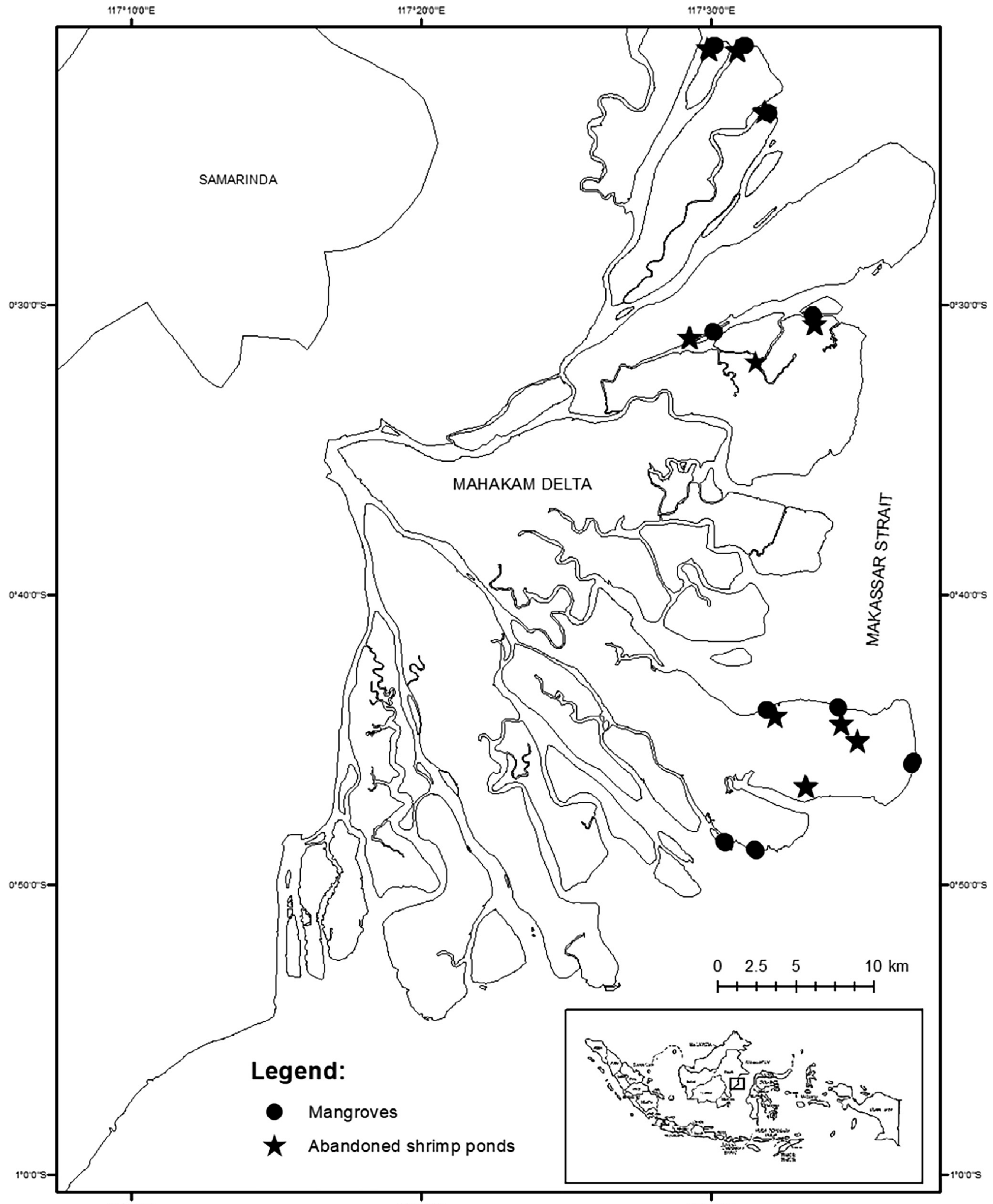

**Fig. 1.** Study plots across the Mahakam Delta, East Kalimantan, Indonesia. The ecosystem carbon stocks of 10 mangroves and 10 abandoned shrimp ponds were sampled in 2013–2014.

shrimp produced. We did not include $CH_4$ emissions from shrimp production with the assumption that high salinity in pond's waters ($>$ 18 ppt) will suppress methanogenesis due to competition by the more energetically efficient sulfate-reducing bacteria (Biswas et al., 2007; Poffenbarger et al., 2011).

The proportion of edible shrimp meat is assumed to be 45% (Kauffman et al., 2017). Based on interviews with the pond owners of our sampling sites, the mean life cycle of a shrimp pond ($P_{life}$) in the

Mahakam Delta was 16 years (ranging from 11 to 21 years).

The major product of the shrimp ponds in the Mahakam Delta is the black tiger shrimp (*Peneaus monodon*) (Bosma et al., 2012) which is a highly valued export commodity for Japan, China, USA and many European countries (Ilman et al., 2009). Based upon our interviews and reports from the Statistics Agency and Marine and Fisheries Agency of Kutai Kartanegara Regency (Badan Pusat Statistik Kabupaten Kutai Kartanegara, 2010, 2013; Dinas Kelautan dan Perikanan Kabupaten Kutai Kartanegara, 2016), we took a mid-point of tiger shrimp production ($P_{prod}$) of 56 kg ha$^{-1}$ yr$^{-1}$ or equivalent to 878 kg ha$^{-1}$ during the mean life cycle of the ponds (16 years). Assuming that the edible meat of shrimp is 45%, then the estimated total productivity of edible tiger shrimp meat during the lifetime of a pond is 395 kg ha$^{-1}$.

In addition to tiger shrimp, pond owners also grow spotted shrimp (*Metapeneaus brevirostris*) (Bosma et al., 2012) and white shrimp (*Litopenaeus vannamei*) in their ponds (Badan Pusat Statistik Kabupaten Kutai Kartanegara, 2010, 2013; Dinas Kelautan dan Perikanan Kabupaten Kutai Kartanegara, 2016). Our interviews with the pond owners showed a mean production of all shrimp species of 123 kg ha$^{-1}$ yr$^{-1}$ (ranging from 90 to 160 kg ha$^{-1}$ yr$^{-1}$) from three harvests per year in the Mahakam Delta. This was close to other studies in the Mahakam Delta who reported a mean shrimp production of 125 kg ha$^{-1}$ yr$^{-1}$ (van Zwieten et al., 2006). A 2016 report on aquaculture shrimp production in the Mahakam Delta reported a mean of 114 kg ha$^{-1}$ yr$^{-1}$ (Dinas Kelautan dan Perikanan Kabupaten Kutai Kartanegara, 2016). If we took a mid-point of the overall shrimp species production at 121 kg ha$^{-1}$ yr$^{-1}$ or equivalent to 1902 kg ha$^{-1}$ during its ponds' lifetime, the edible shrimp meat produced would be estimated at 856 kg ha$^{-1}$ or about twice as much as the tiger shrimp meat production. The shrimp productivity of the Mahakam Delta is lower than global means of shrimp productivity in extensive/low input ponds (Kauffman et al., 2017; Tacon, 2002).

### 2.5. Statistical analysis

Differences in soil properties, biomass and ecosystem carbon stocks among land use types (mangroves and abandoned shrimp ponds) were assessed utilizing analysis of variance (ANOVA). A post-hoc Tukey's honest significant difference (HSD) test was applied to determine the significance of means when the ANOVA result was significant. A Kruskal-Wallis non-parametric significance test was applied when the data were not normally distributed. Data normality was analyzed based on the Shapiro-Wilk tests. A *t*-test was applied to determine the difference of two normally distributed data sets. Statistical analyses were conducted using Microsoft Excel and IBM SPSS Statistics 22.0.

## 3. Results

### 3.1. Aboveground biomass and forest structure

There were great differences in the composition and structure between the mangroves and abandoned shrimp ponds. Mangroves had approximately 3-fold greater tree density (4283 ± 563 ha$^{-1}$; $p < 0.0001$) and 25 times the basal area (45 ± 8 m$^2$ ha$^{-1}$; $p < 0.0001$) of the shrimp ponds (tree density 1316 ± 330 ha$^{-1}$; basal area 2 ± 1 m$^2$ ha$^{-1}$) (Table 1). The majority of the dominant mangrove trees in the Mahakam Delta (*Avicennia alba, Bruguiera sexangula* and *Rhizophora apiculata*) had a diameter range of 5 to 10 cm.

We found significant differences in the aboveground C stocks (trees and downed wood) in the mangroves compared to the shrimp ponds. The mean aboveground C stocks of mangroves (118 Mg ± 8 C ha$^{-1}$) was 8-fold higher than the abandoned shrimp ponds (14 ± 4 Mg C ha$^{-1}$) ($p < 0.0001$). The highest aboveground C stock of mangroves was found in Tunu Island (163 ± 65 Mg C ha$^{-1}$) and the lowest in Lerong Island (84 ± 9 Mg C ha$^{-1}$) (Table 2).

### 3.2. Belowground carbon stocks

The average root carbon stock in the mangroves was 27 ± 4 Mg C ha$^{-1}$ and differed significantly from the abandoned shrimp ponds (2 ± 1 Mg C ha$^{-1}$; $p < 0.0001$). The root biomass accounted for 3% and 0.3% of the total ecosystem carbon stocks in the mangroves and abandoned shrimp ponds respectively. Soil porewater salinity in mangroves ranged from 10 to 25 ppt (mean of 17 ± 0 ppt), while porewater salinity of abandoned shrimp ponds ranged from 10 to 35 ppt (mean of 20 ± 1 ppt; $p < 0.001$; Table 1).

Soil bulk density was significantly higher in abandoned shrimp ponds at 0–15 cm, 15–30 cm and 30–50 cm depths (Tukey HSD; $p < 0.002$, $p = 0.17$ and $p = 0.07$ respectively; Table C). When the data are pooled, we observed significant increases in soil bulk density with depth in the shrimp ponds and mangroves (*t*-test; $p < 0.001$) (Fig. 2a). The mean bulk density in the mangroves differed significantly when testing between the upper (0–100 cm; 0.47 ± 0.02 g cm$^{-3}$) and lower depths (100–300 cm; 0.58 ± 0.02 g cm$^{-3}$) ($p < 0.001$). The same trend was observed in the abandoned ponds, where the mean bulk density at 0–100 cm (0.52 ± 0.02 g cm$^{-3}$) was significantly different to that at 100–300 cm (0.62 ± 0.17 g cm$^{-3}$) (*t*-test; $p = 0.001$).

Soil carbon concentrations tended to decrease with depth (Fig. 2b). In mangroves, we found that the mean soil C concentration at 0–100 cm and 100–300 cm were 8.6 ± 0.8% and 5.4 ± 0.5% respectively (*t*-test; $p < 0.001$). In contrast to the mangroves, there were no significant differences between the mean soil C concentration in the upper 100 cm (4.9 ± 0.2%) and deeper layer (100–300 cm) (4.4 ± 0.1%) in the abandoned shrimp ponds (*t*-test; $p = 0.1$). Generally, we found highly significant differences of soil C concentration between mangroves and abandoned ponds at 0–15 cm, 15–30 cm and 30–50 cm depths (Tukey HSD; $p < 0.0001$, $p = 0.001$ and $p = 0.006$ respectively).

Soil carbon density in the mangroves and abandoned shrimp ponds declined consistently with depth (Fig. 2c). The mean mangrove soil C density at the upper 1 m (0.032 ± 0.001 mg cm$^{-3}$) and deeper layer > 1 m (0.028 ± 0.002 mg cm$^{-3}$) was significantly different (*t*-test; $p = 0.002$). In contrast, there was no significant difference between the upper 1 m and > 1 m soil C density in the abandoned ponds (*t*-test; $p = 0.57$) (Table C). Soil carbon density in mangroves was generally higher than in shrimp ponds at 0–15 cm and 30–50 cm depths (Tukey HSD; $p = 0.001$ and $p = 0.41$ respectively).

Soils at all sites exceeded 3 m in depth, but we limited our measurements of soil carbon pools to 3 m. Using the soil mass equivalence, we found a significant difference between the soils of mangroves to that of the abandoned shrimp ponds ($p < 0.0001$). Due to soil collapse in ponds, the soil mass of the surface 3 m in mangroves was equivalent in mass to a mean soil depth of 191 ± 26 cm in the abandoned shrimp ponds (ranging from 89 to 297 cm) (Table 2). Based upon equivalent soil mass, the mean soil carbon stocks in the mangroves was 879 ± 83 Mg C ha$^{-1}$ and 486 ± 55 Mg C ha$^{-1}$ in shrimp ponds (Table 2).

### 3.3. Total ecosystem carbon stocks

There was a highly significant difference between the total ecosystem carbon stocks of the mangroves and the abandoned shrimp ponds (Kruskal-Wallis; $p < 0.001$). The mean total ecosystem carbon stocks in the mangroves was 1023 ± 87 Mg C ha$^{-1}$ which ranged from 704 ± 86 Mg C ha$^{-1}$ to 1663 ± 222 Mg C ha$^{-1}$. In contrast, the mean ecosystem carbon stocks for abandoned shrimp ponds was 2-fold lower (499 ± 56 Mg C ha$^{-1}$) (Table 2). Soil carbon in mangroves and abandoned shrimp ponds accounted for 86% and 97% of the total ecosystem carbon stocks.

**Table 1**
General description of the sampling sites (mangroves and abandoned shrimp ponds) in the Mahakam Delta, East Kalimantan, Indonesia. Values are mean ± standard error unless noted otherwise.

| Mangrove site | Type | Latitude | Longitude | Dominant species | Salinity (ppt) | Tree density (trees ha$^{-1}$) | Basal area (m$^2$ ha$^{-1}$) |
|---|---|---|---|---|---|---|---|
| Tunu | Mangrove | S 0°30.324′ | E117°33.518′ | *Rhizophora* sp. | 19 | 2412 ± 668 | 19 ± 8 |
| Salette | Mangrove | S 0°30.903′ | E117°30.067′ | *Rhizophora* sp., *Avicennia* sp. | 15 | 3620 ± 1630 | 16 ± 5 |
| Bayur | Mangrove | S 0°43.961′ | E117°31.882′ | *Rhizophora* sp. | 19 | 4013 ± 1823 | 35 ± 12 |
| Labu-labu | Mangrove | S 0°43.892′ | E117°34.396′ | *Bruiguiera sexangula, A. alba* | 21 | 3892 ± 1132 | 24 ± 8 |
| Muara Berau | Mangrove | S 0°21.032′ | E117°30.144′ | *Avicennia marina* | 14 | 3794 ± 1269 | 81 ± 38 |
| Lerong | Mangrove | S 0°21.050′ | E117°31.190′ | *Avicennia alba* | 13 | 5573 ± 1445 | 47 ± 20 |
| Kadutan | Mangrove | S 0°23.369′ | E117°32.005′ | *A. corniculatum/Bruguiera* sp. | 13 | 8479 ± 2249 | 97 ± 51 |
| Rinding | Mangrove | S 0°48.494′ | E117°30.442′ | *Avicennia alba* | 19 | 2120 ± 752 | 32 ± 9 |
| Kanyuran | Mangrove | S 0°48.751′ | E117°31.486′ | *Avicennia alba* | 16 | 4250 ± 1228 | 46 ± 22 |
| Banjar | Mangrove | S 0°45.846′ | E117°36.923′ | *Bruiguiera sexangula* | 21 | 4674 ± 1420 | 54 ± 17 |
| Mean | | | | | 17 | 4283 ± 563 | 45 ± 8 |
| Abandoned pond site | Type | Latitude | Longitude | Dominant species | Salinity (ppt) | Tree density (trees ha$^{-1}$) | Basal area (m$^2$ ha$^{-1}$) |
| Tunu | Abandoned Pond | S 0°30.667′ | E117°33.521′ | Bare ground with natural regeneration (grass and *Rhizophora* sp.) | 21 | 1393 ± 381 | 0.3 ± 0.04 |
| Bayur | Abandoned Pond | S 0°44.204′ | E117°32.18′ | Bare ground with natural regeneration | 24 | 1318 ± 341 | 2 ± 1 |
| Lerong | Abandoned Pond | S 0°21.032′ | E117°30.144′ | Bare ground with wood debris | 18 | 0.00 | 0.00 |
| Kadutan | Abandoned Pond | S 0°23.323′ | E117°31.852′ | Bare ground with natural regeneration (grass) | 16 | 0.00 | 0.00 |
| Muara Berau | Abandoned Pond | S 0°21.187′ | E117°29.896′ | Bare ground with wood debris | 13 | 0.00 | 0.00 |
| Salette | Abandoned Pond | S 0°30.667′ | E117°33.521′ | Abandoned pond with natural regeneration | 14 | 1258 ± 692 | 4 ± 2 |
| Sepatin | Abandoned Pond | S 0°45.009′ | E117°35.029′ | Abandoned pond with natural regeneration | 24 | 1294 ± 218 | 5 ± 1 |
| Benati Dalam | Abandoned Pond | S 0°44.469′ | E117°34.458′ | Abandoned pond with natural regeneration | 21 | 3205 ± 1237 | 1 ± 0.4 |
| Tanjung Nipah | Abandoned Shrimp Pond | S 0°31.953′ | E117°31.514′ | Abandoned pond with natural regeneration | 25 | 2060 ± 707 | 2 ± 1 |
| Perangat | Abandoned Pond | S 0°46.609′ | E117°33.236′ | Bare ground | 23 | 0.00 | 0.00 |
| Mean | | | | | 20 | 1316 ± 330 | 2 ± 1 |

### 3.4. Potential carbon emissions and emission factors

Mangrove conversion to abandoned shrimp ponds resulted in a mean carbon loss of 525 Mg C ha$^{-1}$. Assuming these are losses to the atmosphere, this is a potential carbon emission equivalent of 1925 Mg CO$_2$e ha$^{-1}$. Most of the emissions were derived from soil loss which accounted for about 80% of the total emission (1536 Mg CO$_2$e ha$^{-1}$). The remaining 20% of the emission came from the aboveground loss

**Table 2**
Carbon stocks of mangroves and abandoned shrimp ponds in the Mahakam Delta, Indonesia. AG and BG indicate aboveground and belowground pools respectively. Mean soil depths of abandoned shrimp ponds are based on mangrove soil mass equivalent to 300 cm. Values are mean ± standard error.

| No. | Mangroves | AG (Mg C ha$^{-1}$) | Root (Mg C ha$^{-1}$) | Soil (Mg C ha$^{-1}$) | BG (Mg C ha$^{-1}$) | Ecosystem (Mg C ha$^{-1}$) |
|---|---|---|---|---|---|---|
| 1 | Tunu | 163 ± 65 | 52 ± 21 | 1054 ± 91 | 1106 ± 89 | 1269 ± 112 |
| 2 | Salette | 111 ± 36 | 26 ± 9 | 746 ± 62 | 772 ± 64 | 883 ± 76 |
| 3 | Bayur | 122 ± 25 | 31 ± 7 | 907 ± 27 | 939 ± 32 | 1061 ± 54 |
| 4 | Labu-labu | 135 ± 33 | 28 ± 14 | 783 ± 60 | 811 ± 68 | 946 ± 83 |
| 5 | Muara Berau | 113 ± 38 | 15 ± 4 | 849 ± 117 | 863 ± 115 | 976 ± 108 |
| 6 | Lerong | 84 ± 9 | 29 ± 7 | 656 ± 73 | 685 ± 69 | 769 ± 67 |
| 7 | Kadutan | 146 ± 53 | 29 ± 9 | 867 ± 114 | 896 ± 123 | 1042 ± 174 |
| 8 | Rinding | 111 ± 28 | 16 ± 3 | 795 ± 49 | 810 ± 50 | 921 ± 62 |
| 9 | Kanyuran | 93 ± 35 | 14 ± 7 | 598 ± 78 | 612 ± 77 | 704 ± 86 |
| 10 | Banjar | 99 ± 26 | 33 ± 8 | 1532 ± 209 | 1564 ± 212 | 1663 ± 222 |
| | Mean | 118 ± 8 | 27 ± 4 | 879 ± 83 | 906 ± 85 | 1023 ± 87 |

| No. | Abandoned ponds | AG (Mg C ha$^{-1}$) | Root (Mg C ha$^{-1}$) | Soil (Mg C ha$^{-1}$) | BG (Mg C ha$^{-1}$) | Ecosystem (Mg C ha$^{-1}$) | Mass equivalence to mangrove soil depth (cm) |
|---|---|---|---|---|---|---|---|
| 1 | Tunu | 1 ± 0 | 0.1 ± 0 | 232 ± 51 | 232 ± 51 | 233 ± 50 | 89 |
| 2 | Bayur | 5 ± 9 | 1 ± 0.5 | 240 ± 33 | 241 ± 34 | 245 ± 34 | 109 |
| 3 | Lerong | 3 ± 1 | – | 500 ± 53 | 500 ± 53 | 504 ± 52 | 171 |
| 4 | Kadutan | 15 ± 4 | 0 | 717 ± 26 | 717 ± 26 | 731 ± 26 | 297 |
| 5 | Muara Berau | 3 ± 1 | 0 | 592 ± 46 | 592 ± 46 | 595 ± 45 | 261 |
| 6 | Salette | 33 ± 2 | 4 ± 3 | 374 ± 80 | 377 ± 80 | 410 ± 76 | 94 |
| 7 | Sepatin | 32 ± 9 | 10 ± 1 | 637 ± 67 | 646 ± 66 | 678 ± 59 | 249 |
| 8 | Benati Dalam | 20 ± 15 | 1 ± 1 | 534 ± 84 | 537 ± 84 | 558 ± 81 | 259 |
| 9 | Tanjung Nipah | 3 ± 2 | 1 ± 1 | 367 ± 70 | 368 ± 70 | 371 ± 69 | 110 |
| 10 | Perangat | – | 0.00 | 663 ± 52 | 663 ± 52 | 663 ± 52 | 264 |
| | Mean | 12 ± 4 | 2 ± 1 | 486 ± 55 | 487 ± 55 | 499 ± 56 | 190 ± 26 |

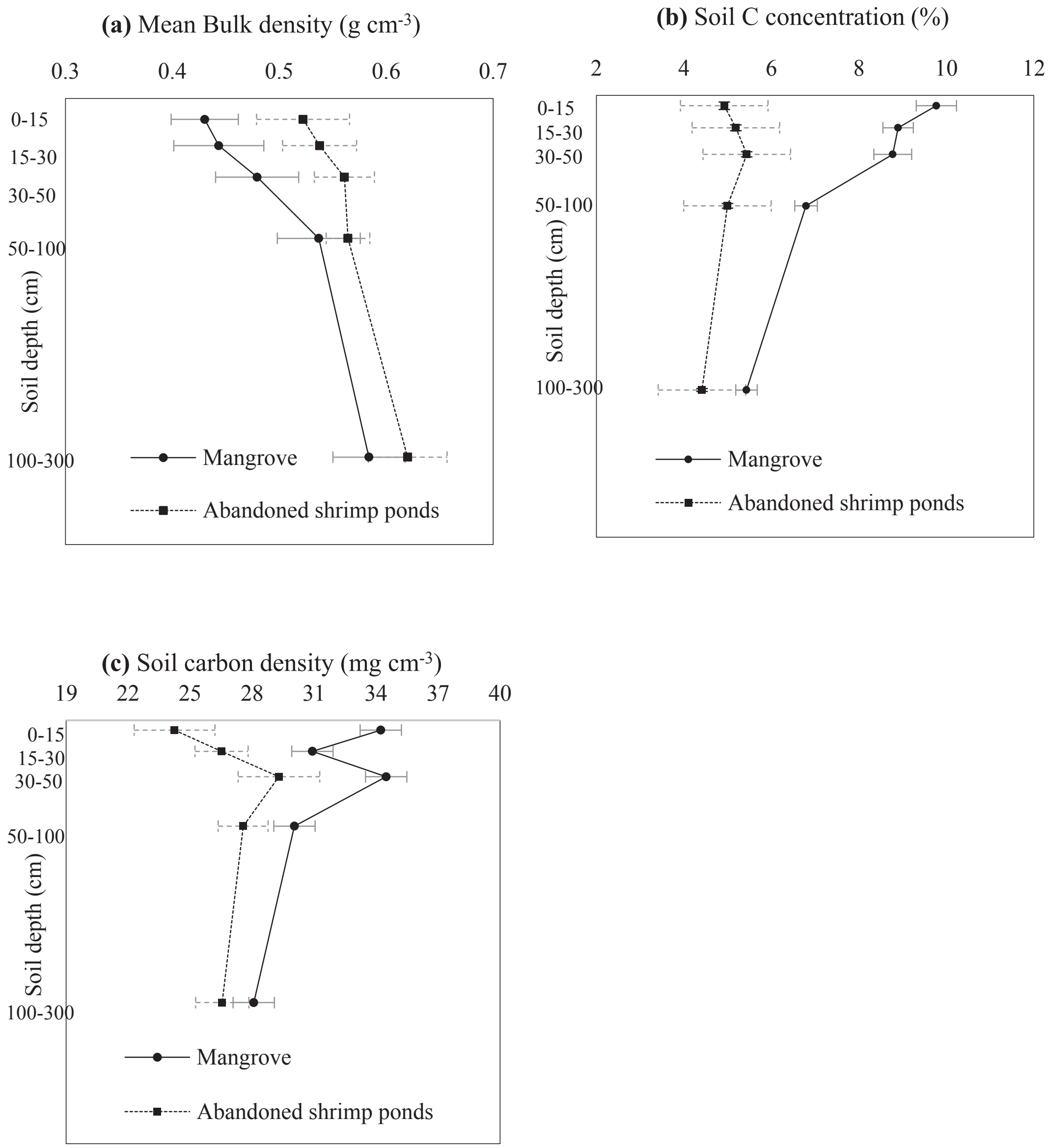

**Fig. 2.** (a) Soil bulk density (g cm$^{-3}$) in mangroves and abandoned ponds at the midpoints of the sampled depths. (b) Soil carbon concentration (%) of mangroves and shrimp ponds decreased with depths. (c) Soil carbon density (mg cm$^{-3}$) in mangroves and abandoned shrimp ponds. Error bars represent the standard error of the mean.

(389 Mg $CO_2$e ha$^{-1}$), assuming 100% was lost to the atmosphere.

Based on our interviews, the average productive life of shrimp ponds in the Mahakam delta was 16 years. Assuming an average period of conversion to abandonment of 16 years, the total mean emission factor arising from mangrove conversion is 33 Mg C ha$^{-1}$ yr$^{-1}$ or 120 Mg $CO_2$e ha$^{-1}$ yr$^{-1}$. The mean mangrove soil emission factor is 25 Mg C ha$^{-1}$ yr$^{-1}$ or 90 Mg $CO_2$e ha$^{-1}$ yr$^{-1}$. But this does not include the carbon that would have been sequestered in the mangrove sites had they not been converted to shrimp ponds.

### *3.5. Land use carbon footprints of shrimp production*

We calculated the land use carbon footprints of 2 types of shrimp production from aquaculture ponds: (1) the black tiger shrimp (*Peneaus monodon*) which is the primary export commodity of the Mahakam Delta; and (2) the overall shrimp production that includes 3 major shrimp species, i.e. tiger shrimp (*Peneaus monodon*), white shrimp (*Litopenaeus vannamei*) and spotted shrimps (*Metapeneaus brevirostris*).

The mean production rates of black tiger shrimp and of all shrimps were 56 kg ha$^{-1}$ yr$^{-1}$ and 121 kg ha$^{-1}$ yr$^{-1}$ respectively. For the 16 year life of a shrimp pond the total black tiger shrimp production would be 878 kg ha$^{-1}$. If $N_2O$ emissions are 503.6 g $CO_2$e per kg of shrimp produced (Hu et al., 2012), then the total $N_2O$ emissions produced by 878 kg ha$^{-1}$ of tiger shrimp is 0.4 Mg $CO_2$e ha$^{-1}$. If 0.4 Mg $CO_2$e ha$^{-1}$ of $N_2O$ emissions was produced during the black tiger shrimp production and added to the potential carbon loss from mangrove conversion (1925 Mg $CO_2$e ha$^{-1}$), the average $CO_2$e emissions from every kg of tiger shrimp produced in the Mahakam Delta would be 4874 kg $CO_2$e.

When the same method was applied to estimate all shrimp production, we obtain a mean land use carbon footprint of 2250 kg $CO_2$e for every kg of shrimp produced.

## 4. Discussion

### *4.1. Aboveground carbon stocks and structure*

The mean aboveground carbon stocks of mangroves in this study

(118 ± 8 Mg C $ha^{-1}$) accounted for 11% of the total ecosystem carbon stocks and are higher than IPCC default value for aboveground carbon stocks for mangroves in tropical wet region (86.4 Mg C $ha^{-1}$; IPCC, 2014). Compared to other mangroves, the mean aboveground carbon stocks in the Mahakam Delta is similar to the tall mangroves in Pantanos de Centla, Mexico (Kauffman et al., 2015), Yucatan-Mexico (Adame et al., 2013) and India (Bhomia et al., 2016). The mean aboveground carbon stocks of the Mahakam Delta were at the low end of the mean of the aboveground carbon stocks of Indonesian mangroves (211 Mg C $ha^{-1}$) (Murdiyarso et al., 2015).

We found that abandoned shrimp ponds had higher soil porewater salinity than the mangroves with mean salinity differences of 3 ppt. The seawater elements such as Ca, Mg, K and Na were introduced during shrimp raising activities and all the salts persist in the soil after pond's abandonment. Lack of tidal flushing and evaporation triggered salt crystallization and accumulation at the pond soils which can raise water salinity to levels unfavorable for shrimp growth as well for the plants (Banerjee et al., 2013; Towatana et al., 2002). Since the salinity levels in the abandoned ponds of the Mahakam Delta are still favorable for shrimp (less than 25 ppt), there were likely other factors that has led to abandonment of the ponds (e.g. disease outbreaks and dyke collapse due to high floods).

### 4.2. Soils

We observed higher bulk density in the abandoned shrimp ponds than the mangroves. The increase in bulk density was also found in deforested mangrove sites in Kenya (Lang'at et al., 2014). Studies in mangrove soils have reported that tree mortality, organic matter decomposition and physical compaction resulted in surface elevation losses in mangrove soils (Cahoon et al., 2003; Krauss et al., 2010, 2014) which are reflected by an increase in bulk density (Lang'at et al., 2014). Similarly, studies in upland forests have shown the impacts of deforestation resulting in increased bulk density, decreased soil porosity, infiltration rates and hydraulic conductivity leading to soil compaction (Batey and McKenzie, 2006; Germer et al., 2010).

We also found highly significant differences in soil carbon concentration between the mangroves and abandoned ponds ($p < 0.001$) at depths to 3 m. This underscores the importance of sampling the entire profile or at least to depths of 3 m in order to more thoroughly describe influences of land use on carbon dynamics.

Comparing the mean soil C stocks in the upper 1 m between mangroves (317 ± 26 Mg C $ha^{-1}$) and abandoned pond sites (273 ± 13 Mg C $ha^{-1}$) resulted in soil loss of 44 Mg C $ha^{-1}$ or 9 times lower than the soil loss measured up to 3 m (393 Mg C $ha^{-1}$). Limiting soil loss to 1 m or less resulted in underestimates of the soil C stocks and carbon losses as differences in soil C concentration and bulk density were found below this depth.

Similarly, limiting the soil carbon stock measurements to 3 m results in an underestimate of the ecosystem carbon stocks of these deltaic mangroves. For example, we sampled the soils to 5 m depth in the Bayur mangrove and abandoned pond sites. The soil carbon concentrations at 3.7–3.75 m and 4.7–4.75 m depth in Bayur mangrove were 2.9% and 2.6% respectively. Similar values were obtained from the mean soil carbon concentrations in the abandoned ponds at both depths (2.5% and 2.8% respectively). The total soil carbon stocks to a depth of 5 m were 1257 Mg C $ha^{-1}$ (compared to soil C stocks to 3 m of 879 Mg C $ha^{-1}$). Inclusion of soil carbon at 3–5 m depth to the ecosystem carbon in Bayur site would increase the ecosystem carbon stocks substantially from 1061 Mg C $ha^{-1}$ to 1410 Mg C $ha^{-1}$. This suggests that measurements of soil carbon stocks to 3 m in mangroves of deep alluvium is an underestimate of at least 33% of the total ecosystem carbon stocks.

Mangroves had higher soil carbon concentration compared to shrimp ponds at 0–15 cm, 15–30 cm, 30–50 cm and 50–100 cm depths ($p < 0.0001$, $p = 0.001$, $p = 0.006$ and $p = 0.56$ respectively; Fig. 2b). The decline in the amount of organic matter in the abandoned ponds was likely due to decomposition of the organic matter in soils especially during periods when the ponds were drained after shrimp harvests and following abandonment (Turner, 2004; Towatana et al., 2002). Draining and limiting tidal flows likely created aerobic conditions favorable for carbon oxidation.

The mean mangrove soil carbon stocks in the Mahakam Delta (879 ± 83 Mg C $ha^{-1}$) are similar to the average mangrove soil carbon stocks across many sites in Indonesia (849 ± 323 Mg C $ha^{-1}$; Murdiyarso et al., 2015). Moreover, our results are substantially higher than the IPCC global default value for mangrove soils (471 Mg C $ha^{-1}$; IPCC, 2014) (Table 3).

When mangroves are converted to shrimp ponds a dramatic decrease in soil carbon occurs. The clearing of mangrove trees and draining of mangrove soils led to a 45% reduction of the soil carbon stocks. This is equivalent to 393 Mg C $ha^{-1}$ (1442 Mg $CO_2$e $ha^{-1}$) of soil loss. Unlike upland forests where only the top 30 cm of soils were considered to be susceptible to carbon losses due to land use change (IPCC, 2006), drainage and oxidation of hydric soils in tropical wetlands affected the deeper soil layers (Hooijer et al., 2006; Kauffman et al., 2015). The losses reported here are similar or even less than the losses resulted from mangrove conversion to abandoned shrimp ponds in the Dominican Republic (Kauffman et al., 2014) and conversion to pastures in Mexico (Kauffman et al., 2015).

### 4.3. Potential carbon emissions and emission factors

The losses due to land cover change in this study (1925 Mg $CO_2$e $ha^{-1}$) exceed that of early estimates of global emissions estimates from Pendleton et al. (2012) (935 Mg $CO_2$e $ha^{-1}$) and Donato et al. (2011) (411–1439 Mg $CO_2$e $ha^{-1}$). The potential emissions reported here are also greater than emissions arising from mangrove conversion to cattle pasture in Mexico (1464 Mg $CO_2$e $ha^{-1}$; Kauffman et al., 2015) and exceeds the IPCC global default value for the entire soil carbon stock (i.e, 525 Mg C $ha^{-1}$ compared to 471 Mg C $ha^{-1}$; IPCC, 2014). Different estimates of the ecosystem carbon loss resulted from different approaches or assumptions used in those studies. The Kauffman et al. (2015) calculation was based on mass equivalence loss from the top 1 m of mangrove soils. Pendleton et al. (2012) and Donato et al. (2011) estimates were not based on actual measurements but on an assumption that 25% soil was lost from the top 30 cm. Similarly, the land use change emissions reported in Järviö et al. (2017) were based on IPCC (2006) default value at 1 m soil depth.

A recent study on the extent of mangroves in the Mahakam Delta using 2015 radar Sentinel-I imageries reported that the mangrove deforestation rate from 1994 to 2015 was 2832 ha $yr^{-1}$ (Aslan, 2017). Thus, the annual $CO_2$ emissions arising from mangrove conversion to shrimp ponds in the entire Mahakam Delta is estimated to be 0.005 Pg $CO_2$e $yr^{-1}$.

FAO (2007) reported that Indonesia's total mangrove area in 2005 was 2.9 Mha with an average deforestation rate of 50,000 ha $yr^{-1}$ from 2000 to 2005. Based upon these data and assuming that deforestation rate was constant over the 20 years presented above, the Mahakam Delta that covers only 2% of Indonesia's mangrove area, accounted for 6% of Indonesia's annual mangrove deforestation rate. Assuming that the $CO_2$ emissions following land use/land cover change in Indonesian mangroves would be similar to the emissions in the Mahakam Delta, the total potential $CO_2$ emissions from mangrove deforestation in Indonesia would be 0.096 Pg $CO_2$e $yr^{-1}$. This number is at the lower end than what had been estimated by Murdiyarso et al. (2015) (0.07–0.21 Pg $CO_2$e $yr^{-1}$), which used the assumption that the emissions from mangrove deforestation was similar to the higher rates measured in the abandoned shrimp ponds in the Dominican Republic (Kauffman et al., 2014).

It is important to quantify longevity of the shrimp ponds in order to determine the magnitude of the carbon emissions relative to the productivity of shrimp produced. The longevity of shrimp ponds in the Mahakam Delta (16 years with a range of 11–21 years) was longer than the global means reported by Kauffman et al. (2017). This estimate of pond longevity is based upon interviews with pond owners, personnel of local NGOs and district fisheries managers. Setiawan et al. (2015) also reported the lifetime of shrimp ponds in the Mahakam Delta to range from 15 to 25 years. Based upon our interviews and radar analysis from 1994 to 2005 (Aslan, 2017), some ponds that were established in the 90s are still active. The main factors resulting in pond abandonment in the Mahakam Delta included infrastructure failure (i.e. dyke collapse) and low shrimp productivity due to disease outbreaks. Globally, common causes of abandonment include disease outbreaks, soil acidification, pollution and market conditions (Rönnbäck, 1999; Tacon, 2002).

If the average time since mangrove deforestation was 16 years, the annual carbon emissions would be 33 Mg C $ha^{-1}$ $yr^{-1}$ or equivalent to 120 Mg $CO_2$e $ha^{-1}$ $yr^{-1}$. This number is substantially higher than IPCC mean emission factor value (2 Mg C $ha^{-1}$ $yr^{-1}$) for organic wetlands soils after drainage (IPCC, 2006) and similar to emission factor from peat swamp conversion to oil palm plantations in West Kalimantan (127 Mg $CO_2$e $ha^{-1}$ $yr^{-1}$; Basuki, 2017).

### 4.4. Land use carbon footprints of shrimp production

The mean production rates of shrimp in the Mahakam Delta (121 kg $ha^{-1}$ $yr^{-1}$) are dramatically lower than reported production estimates of 600–1000 kg $ha^{-1}$ $yr^{-1}$ for traditional aquaculture pond production in Indonesia (Setiawan et al., 2015). This low shrimp productivity coupled with a high emission from land conversion resulted in a land use carbon footprint of 4874 kg $CO_2$e for every kg of tiger shrimp produced and 2250 kg $CO_2$e for all shrimp combined. Our estimation of the land use carbon footprint of shrimp is significantly higher than the mean ecosystem carbon footprint of shrimp in several tropical countries (1603 kg $CO_2$e per kg of shrimp; Kauffman et al., 2017) and the Mekong Delta, Vietnam (184–282 kg $CO_2$e per kg of shrimp; Järviö et al., 2017). Although our potential emissions from land use change is in the same range as reported by Kauffman et al. (2017) (1894 Mg $CO_2$e $ha^{-1}$ $yr^{-1}$), higher ecosystem carbon footprint values than Kauffman et al. (2017) are due to their estimate of a shorter lifetime of the shrimp ponds (9 years) but with higher rates of shrimp production (275 kg of shrimp per year). The lower value reported by Järviö et al. (2017) are due to very low land use change GHG emissions and the assumption of a long steady productive life time of shrimp farming (50 years) in the Mekong Delta, Vietnam. Järviö et al. (2017) also only included emissions to 1 m depth which is an underestimate of the total soil losses and emissions from land use change.

To gain a perspective of the carbon emissions generated from shrimp production, we compared these emissions to common human activities. If 8887 g of $CO_2$ are emitted from combustion of 1 gallon of gasoline in automobiles (Federal Register, 2010), then the emissions from the production of 1 kg of black tiger shrimp is equivalent to burning 548 gallons or 2074 L of gasoline. Similarly, the carbon footprint of 1 kg of all shrimp produced would be equivalent to 253 gallons or 958 L of gasoline consumed by automobiles.

Including carbon losses from land use into the carbon footprint calculation resulted in very large increases in estimates compared to other studies which do not include carbon losses from land use/cover change. For example, carbon footprints of shrimp that do not include land use was 3–15 kg $CO_{2\text{-}e}$ per kg of shrimp (Nijdam et al., 2012). This highlights the importance of including carbon losses from deforestation or other land cover changes to the carbon footprint calculation (Henriksson et al., 2015; Järviö et al., 2017; Jonell and Henriksson, 2015; Kauffman et al., 2017).

Beyond the multitude ecosystem services that would be protected, conservation of all remaining mangroves would be a valuable strategy for climate change mitigation. This is because of the great capacity for carbon sequestration and the high vulnerability to loss through land conversion. The ecosystem carbon loss from mangrove conversion was 525 Mg C $ha^{-1}$ of which 393 Mg C $ha^{-1}$ came through depletion of soil carbon stocks. Recovery of this lost carbon would not be regained in a reasonable amount of time even if the sites were restored. Alongi (2014) reported that the mean carbon burial rate in mangroves to be 5 mm $yr^{-1}$ or 1.74 Mg C $ha^{-1}$. If true, then 16 years of shrimp pond use in the Mahakam Delta resulted in a carbon loss equivalent to 226 years of soil carbon accumulation in natural mangroves.

## 5. Conclusions

Our study provides an accuracy improvement in soil C stocks estimation by measuring soil C stocks up to 3 m or beyond. This is important in climate change mitigation for two reasons: (1) sampling only to 1 m underestimates the carbon stocks and therefore the values of mangroves in climate change mitigation, and (2) limiting sampling to depths ≥1 m results in underestimates in the emissions of greenhouse gases when mangrove ecosystems are converted to other uses. The carbon loss associated with the low productivity of shrimp production results in a large land use carbon footprint underscoring the significant loss in the ecosystem service of carbon sequestration. In addition, there are many additional values maintained with the protection and conservation of these blue carbon ecosystems.

## Acknowledgements

This study was part of the Kalimantan Wetlands Climate Change Study (KWACS) funded by the United States Agency for International Development (USAID). We wish to thank Dr. Steven Perakis and Dr. Dana Warren (Oregon State University) for their support and feedback on reviewing this manuscript. Many thanks to Sutanto, Suriyanto, Wahyu Sandus and Erwansa who assisted in field data collection. We also thank the Ministry of Environment and Forestry of Indonesia and Bogor Agricultural University for their help in soil and wood laboratory.

## A. Appendix

**Table A.** Biomass allometric equations for mangrove species used in this study.

| Nr. | Species | Allometric equation | $R^2$ | Source | Data Origin |
|---|---|---|---|---|---|
| 1 | *Rhizophora apiculata* | Wood biomass = 0.0695Dˆ2.644 * ρ | 0.89 | Kauffman and Cole (2010) | Micronesia |
| | | LOG Branch biomass = −2.02 + 2.37logD | 0.88 | Amira (2008) | West Borneo, Indonesia |
| | | LOG Leaves biomass = −1.68 + 1.92logD | 0.87 | Ong et al. (2004) | Malaysia |
| | | Root biomass = 0.00698 * Dˆ2.61 | 0.99 | Ong et al. (2004) | Malaysia |
| | | Stilt root biomass = 0.0209 * Dˆ2.55 | 0.84 | Ong et al. (2004) | Malaysia |

| | | | | | |
|---|---|---|---|---|---|
| 2 | *Rhizophora mucronata* | AGB biomass = 0.251ρ Dˆ2.46 | 0.98 | Komiyama et al. (2005) | Indonesia & Thailand |
| | | Root biomass = 0.199ρˆ0.899 Dˆ2.22 | 0.95 | Komiyama et al. (2005) | Indonesia & Thailand |
| | | ρ = 0.701 ± 0.033 | | | |
| 3 | *Bruguiera gymnorrhiza* | LOG AGB Biomass = −0.7309 + 2.3055 log D | 0.99 | Clough and Scott, 1989 | Australia |
| | | Root biomass = 0.199 * p * 0.899 * Dˆ2.22 | 0.95 | Komiyama et al. (2005) | Thailand, Indonesia |
| 4 | *Bruguiera sexangula* | Stem biomass = 0.8902 (Dˆ2 * H)ˆ0.0796 | 0.98 | Kusmana et al. (1992) | East Sumatera, Indonesia |
| | | Branch&twigs biomass = 1.0293(Dˆ2 * H)ˆ0.0126 | 0.95 | Kusmana et al. (1992) | East Sumatera, Indonesia |
| | | Leaves biomass = 0.073(Dˆ2 * H)ˆ0.0021 | 0.88 | Kusmana et al. (1992) | East Sumatera, Indonesia |
| | | Root biomass = 0.199 * p * 0.899 * Dˆ2.22 | 0.95 | Komiyama et al. (2005) | Thailand, Indonesia |
| 5 | *Avicennia marina* | AGB = 0.185 * DBHˆ2.352 | 0.98 | Dharmawan and Siregar, 2008 | West Java, Indonesia |
| | | Root biomass = 0.168 * Dˆ1.794 | 0.98 | Dharmawan and Siregar (2008) | West Java, Indonesia |
| | | Total biomass = 0.291 * Dˆ2.260 | 0.86 | Dharmawan and Siregar (2008) | West Java, Indonesia |
| 6 | *Sonneratia alba* | Wood biomass = 0.3841Dˆ2.101 * ρ | 0.92 | Kauffman and Cole (2010) | Micronesia |
| | | Root biomass = 0.199 * p * 0.899 * Dˆ2.22 | 0.95 | Komiyama et al. (2005) | Thailand, Indonesia |
| 7 | *Lumnitzera racemosa* | WTOP = 0.184 * DBHˆ2.384 | 0.98 | Kangkuso et al. (2015) | South Sulawesi, Indonesia |
| | | Root biomass = 0.199 * p * 0.899 * Dˆ2.22 | 0.95 | Komiyama et al. (2005) | Thailand, Indonesia |
| 8 | Common equation for mangrove AGB biomass | WTOP = 0.251 * p * Dˆ2.46 | 0.98 | Komiyama et al. (2005) | Thailand, Indonesia |
| 9 | Common equation for mangrove root biomass | WR = 0.199 * p * 0.899 * Dˆ2.22 | 0.95 | Komiyama et al. (2005) | Thailand, Indonesia |

## B. Detailed methods of carbon stock and emission measurements

### B.1. Measurements of standing dead trees and downed wood

Standing dead trees were classified to three classes following methods given by Kauffman and Donato (2012): Status 1 was assigned for dead trees without leaves; Status 2 for dead trees without secondary branches; and Status 3 for dead trees with only the trunk. Status 1 - dead tree biomass was estimated using the total plant biomass minus the leaves biomass (leaf biomass equation provided by Clough and Scott (1989) and Komiyama et al. (2005)) or by subtracting a constant of 2.5% of the aboveground biomass of the tree (Kauffman and Donato, 2012). Status 2 - was estimated using the total plant biomass minus secondary branches. A common method was to subtract a total of 10–20% of biomass including the leaves and some branches or adjusted to specific settings (Kauffman and Donato, 2012). Status 3 - was estimated by calculating the tree volume of truncated cone using the equation described by Kauffman and Donato (2012).

Downed wood of different sizes were measured using the planar intersect technique. The diameter of each woody debris that intersects a vertical sampling plane is measured (Kauffman and Donato, 2012; Van Wagner, 1968). Four transects of 14 m in length were established in the center of each plot. The first transect was set at an angle of 45° from the main transect and the other three were set 90° clockwise from the first transect. Based on the diameter, they were classified into small debris (2.5–7.5 cm) which was measured along the last 5 m of the transect; and large debris (> 7.5 cm) which was measured along 12 m from the second meter of the transect (Kauffman and Donato, 2012). Specific gravity of wood debris samples (Table 2.2) were measured in the lab and used to calculate the biomass using the formula outlined in Kauffman and Donato (2012) and converted to C stock using a factor of 0.47 which was derived from the mean C concentration of 386 samples of wood from all mangrove species measured in this study.

### B.2. Ecosystem C stocks

The ecosystem carbon stock was estimated by summing all carbon pools (IPCC, 2006):

$$\text{Total carbon pool (Mg C ha}^{-1}\text{)} = C_{\text{aboveground}} + C_{\text{wood debris}} + C_{\text{soil}} + C_{\text{belowground}} \tag{B1}$$

where

Total carbon pool = Total ecosystem carbon pools ($\mathrm{Mg\,C\,ha^{-1}}$)
$C_{\mathrm{aboveground}}$ = Total aboveground vegetation carbon pool ($\mathrm{Mg\,C\,ha^{-1}}$)
$C_{\mathrm{dead\ wood}}$ = Total dead wood carbon pool ($\mathrm{Mg\,C\,ha^{-1}}$)
$C_{\mathrm{soil}}$ = Total soil carbon pool ($\mathrm{Mg\,C\,ha^{-1}}$)
$C_{\mathrm{belowground}}$ = Total belowground plant mass carbon pool ($\mathrm{Mg\,C\,ha^{-1}}$)

### *B.3. Emissions from conversion of mangroves into abandoned shrimp ponds*

The potential emissions arising from mangrove conversion into abandoned shrimp ponds were calculated by stock-difference method to estimate emissions due to land use change (IPCC, 2006; Kauffman et al., 2015).

$$\Delta C_{LU} = \Delta C_{AB} + \Delta C_{BB} + \Delta C_{DW} + \Delta C_{SOC} \qquad \text{(B2)}$$

where
$C_{LU}$ = Change in carbon stocks due to land use
$C_{AB}$ = Change in aboveground biomass
$C_{BB}$ = Change in belowground biomass
$C_{DW}$ = Change in dead wood
$C_{SOC}$ = Change in soil organic carbon.

#### *B.3.1. Land use carbon footprints of shrimp production*

We used the following equation to determine the carbon footprints of shrimp produced in aquaculture ponds resulting from mangrove conversions (Kauffman et al., 2017):

$$FP_c = \left(C_{conv} + e_{N_2O}\right)/(P_{prod} \times P_{life} \times Cf_{meat}) \qquad \text{(B3)}$$

where
$FP_c$ = Land use carbon footprint
$C_{conv}$ = Total loss of ecosystem C (Mg $CO_2$e) due to land cover change
$e_{N2O}$ = $N_2O$ emissions during active production phases in shrimp ponds (Mg $CO_2$e)
$P_{prod}$ = Production of shrimp (Mg of shrimp $\mathrm{year^{-1}}$)
$P_{life}$ = Productive life of the land use (years)
$Cf_{meat}$ = Proportion (%) of the shrimp that is meat

**Table C.** Soil bulk density, C concentration, C density and C stocks of soils in the mangroves and abandoned shrimp ponds in the Mahakam Delta, East Kalimantan. Values are mean ± standard error unless noted otherwise. The mean values represent bulk density, C concentration and C density. The total soil C stock is the sum of the C stocks from all soil depths ± standard error. Total soil carbon pool ($\mathrm{Mg\ C\ ha^{-1}}$) normalized to mineral soil mass. (Source: this study)

| SITE | Soil depth (cm) | Bulk density ($\mathrm{g\ cm^{-3}}$) | Carbon concentration (%) | C density ($\mathrm{g\ cm^{-3}}$) | C stock ($\mathrm{Mg\ C\ ha^{-1}}$) |
|---|---|---|---|---|---|
| Tunu mangrove | 0-15 | 0.40 ± 0.04 | 8.75 ± 1.2 | 0.03 ± 0.005 | 51 ± 8 |
| | 15-30 | 0.43 ± 0.03 | 10.00 ± 1.2 | 0.04 ± 0.005 | 62 ± 79 |
| | 30-50 | 0.41 ± 0.03 | 10.57 ± 0.9 | 0.04 ± 0.002 | 84 ± 4 |
| | 50-100 | 0.59 ± 0.07 | 5.71 ± 1.3 | 0.03 ± 0.002 | 146 ± 8 |
| | 100-300 | 0.52 ± 0.07 | 7.56 ± 1.7 | 0.04 ± 0.005 | 710 ± 105 |
| Mean | | 0.47 ± 0.04 | 8.52 ± 0.87 | 0.04 ± 0.00 | 1054 ± 91 |
| Salette mangrove | 0-15 | 0.46 ± 0.02 | 6.74 ± 0.5 | 0.03 ± 0.002 | 46 ± 2 |
| | 15-30 | 0.52 ± 0.01 | 5.48 ± 0.2 | 0.03 ± 0.001 | 43 ± 2 |
| | 30-50 | 0.53 ± 0.02 | 5.17 ± 0.4 | 0.03 ± 0.002 | 55 ± 4 |
| | 50-100 | 0.62 ± 0.03 | 4.27 ± 0.6 | 0.03 ± 0.003 | 131 ± 15 |
| | 100-300 | 0.62 ± 0.05 | 3.78 ± 0.1 | 0.02 ± 0.002 | 471 ± 47 |
| Mean | | 0.55 ± 0.03 | 5.09 ± 0.51 | 0.03 ± 0.00 | 746 ± 62 |
| Bayur mangrove | 0-15 | 0.42 ± 0.04 | 10.31 ± 0.8 | 0.04 ± 0.004 | 63 ± 6 |
| | 15-30 | 0.37 ± 0.04 | 10.29 ± 0.8 | 0.04 ± 0.003 | 55 ± 4 |
| | 30-50 | 0.37 ± 0.04 | 10.93 ± 1.0 | 0.04 ± 0.003 | 77 ± 5 |
| | 50-100 | 0.41 ± 0.05 | 8.19 ± 0.8 | 0.03 ± 0.002 | 159 ± 10 |
| | 100-300 | 0.58 ± 0.02 | 4.75 ± 0.1 | 0.03 ± 0.001 | 553 ± 19 |
| Mean | | 0.43 ± 0.04 | 8.89 ± 1.13 | 0.04 ± 0.00 | 907 ± 27 |
| Labu-labu mangrove | 0-15 | 0.26 ± 0.05 | 18.83 ± 4.1 | 0.04 ± 0.004 | 61 ± 6 |
| | 15-30 | 0.30 ± 0.06 | 18.47 ± 5.5 | 0.05 ± 0.012 | 68 ± 18 |
| | 30-50 | 0.41 ± 0.09 | 11.45 ± 3.9 | 0.03 ± 0.004 | 61 ± 9 |
| | 50-100 | 0.46 ± 0.03 | 6.36 ± 0.9 | 0.03 ± 0.004 | 147 ± 21 |
| | 100-300 | 0.49 ± 0.06 | 4.78 ± 0.4 | 0.02 ± 0.001 | 447 ± 26 |
| Mean | | 0.39 ± 0.04 | 11.98 ± 2.94 | 0.03 ± 0.00 | 783 ± 60 |
| Muara Berau | 0-15 | 0.48 ± 0.03 | 5.29 ± 0.13 | 0.03 ± 0.001 | 38 ± 2 |

| | | | | | |
|---|---|---|---|---|---|
| mangrove | 15-30 | 0.53 ± 0.02 | 4.85 ± 0.28 | 0.03 ± 0.001 | 38 ± 1 |
| | 30-50 | 0.57 ± 0.03 | 5.57 ± 0.53 | 0.03 ± 0.002 | 62 ± 3 |
| | 50-100 | 0.57 ± 0.02 | 4.84 ± 0.35 | 0.03 ± 0.001 | 137 ± 5 |
| | 100-300 | 0.60 ± 0.04 | 4.73 ± 0.76 | 0.03 ± 0.006 | 574 ± 119 |
| Mean | | 0.55 ± 0.02 | 5.06 ± 0.16 | 0.03 ± 0.00 | 849 ± 117 |
| Lerong mangrove | 0-15 | 0.54 ± 0.04 | 3.83 ± 0.4 | 0.02 ± 0.002 | 30 ± 2 |
| | 15-30 | 0.60 ± 0.06 | 3.75 ± 0.7 | 0.02 ± 0.003 | 31 ± 4 |
| | 30-50 | 0.64 ± 0.04 | 3.97 ± 0.9 | 0.02 ± 0.003 | 48 ± 7 |
| | 50-100 | 0.57 ± 0.06 | 4.55 ± 0.7 | 0.02 ± 0.002 | 120 ± 11 |
| | 100-300 | 0.76 ± 0.04 | 2.78 ± 0.4 | 0.02 ± 0.004 | 426 ± 71 |
| Mean | | 0.62 ± 0.04 | 3.78 ± 0.29 | 0.02 ± 0.00 | 656 ± 73 |
| Kadutan mangrove | 0-15 | 0.5 ± 0.04 | 5.06 ± 0.3 | 0.03 ± 0.002 | 38 ± 3 |
| | 30-50 | 0.45 ± 0.02 | 6.82 ± 0.21 | 0.03 ± 0.001 | 61 ± 2 |
| | 50-100 | 0.58 ± 0.02 | 4.63 ± 0.39 | 0.03 ± 0.002 | 135 ± 11 |
| | 100-300 | 0.62 ± 0.04 | 5.11 ± 1.36 | 0.03 ± 0.006 | 594 ± 113 |
| Mean | | 0.53 ± 0.03 | 5.41 ± 0.38 | 0.03 ± 0.00 | 867 ± 114 |
| Rinding mangrove | 0-15 | 0.52 ± 0.03 | 5.47 ± 0.46 | 0.03 ± 0.003 | 43 ± 4 |
| | 15-30 | 0.56 ± 0.04 | 5.34 ± 0.45 | 0.03 ± 0.002 | 44 ± 4 |
| | 30-50 | 0.57 ± 0.07 | 5.44 ± 0.43 | 0.03 ± 0.004 | 61 ± 8 |
| | 50-100 | 0.64 ± 0.1 | 5.26 ± 0.43 | 0.03 ± 0.004 | 163 ± 22 |
| | 100-300 | 0.59 ± 0.06 | 4.31 ± 0.54 | 0.02 ± 0.002 | 484 ± 32 |
| Mean | | 0.57 ± 0.02 | 5.17 ± 0.22 | 0.03 ± 0.00 | 795 ± 49 |
| Kanyuran mangrove | 0-15 | 0.46 ± 0.04 | 4.41 ± 0.62 | 0.02 ± 0.002 | 29 ± 2 |
| | 15-30 | 0.47 ± 0.07 | 4.22 ± 0.46 | 0.02 ± 0.003 | 31 ± 5 |
| | 30-50 | 0.60 ± 0.04 | 5.63 ± 1.68 | 0.04 ± 0.013 | 72 ± 26 |
| | 50-100 | 0.66 ± 0.07 | 3.81 ± 0.33 | 0.02 ± 0.003 | 121 ± 13 |
| | 100-300 | 0.68 ± 0.04 | 2.68 ± 0.52 | 0.02 ± 0.003 | 345 ± 53 |
| Mean | | 0.57 ± 0.05 | 4.15 ± 0.48 | 0.02 ± 0.00 | 598 ± 78 |
| Banjar mangrove | 0-15 | 0.25 ± 0.07 | 29.03 ± 2.48 | 0.08 ± 0.03 | 114 ± 40 |
| | 15-30 | 0.16 ± 0.02 | 21.14 ± 3.88 | 0.04 ± 0.007 | 53 ± 11 |
| | 30-50 | 0.25 ± 0.04 | 22.21 ± 1.42 | 0.05 ± 0.009 | 108 ± 19 |
| | 50-100 | 0.26 ± 0.04 | 20.30 ± 2.60 | 0.05 ± 0.003 | 243 ± 15 |
| | 100-300 | 0.37 ± 0.03 | 13.82 ± 2.61 | 0.05 ± 0.011 | 1013 ± 221 |
| Mean | | 0.26 ± 0.03 | 21.3 ± 2.42 | 0.05 ± 0.01 | 1532 ± 209 |
| Tunu pond | 0-15 | 0.73 ± 0.04 | 3.02 ± 0.42 | 0.02 ± 0.002 | 32 ± 3 |
| | 15-30 | 0.63 ± 0.06 | 4.49 ± 0.71 | 0.03 ± 0.002 | 40 ± 4 |
| | 30-50 | 0.64 ± 0.04 | 3.96 ± 0.52 | 0.02 ± 0.003 | 49 ± 5 |
| | 50-100 | 0.58 ± 0.04 | 4.24 ± 0.50 | 0.02 ± 0.003 | 85 ± 27 |
| | 100-300 | 0.82 ± 0.04 | 3.57 ± 0.26 | 0.03 ± 0.001 | 26 ± 26 |
| Mean | | 0.68 ± 0.04 | 3.86 ± 0.26 | 0.03 ± 0.00 | 232 ± 51 |
| Bayur Pond | 0-15 | 0.53 ± 0.03 | 3.24 ± 0.07 | 0.02 ± 0.001 | 26 ± 1 |
| | 15-30 | 0.71 ± 0.01 | 3.44 ± 0.20 | 0.02 ± 0.001 | 37 ± 2 |
| | 30-50 | 0.71 ± 0.05 | 3.88 ± 0.14 | 0.03 ± 0.001 | 55 ± 3 |
| | 50-100 | 0.60 ± 0.05 | 4.46 ± 0.12 | 0.03 ± 0.002 | 93 ± 13 |
| | 100-300 | 0.60 ± 0.03 | 4.72 ± 0.33 | 0.03 ± 0.002 | 29 ± 29 |
| Mean | | 0.63 ± 0.04 | 3.95 ± 0.28 | 0.02 ± 0.00 | 240 ± 33 |
| Lerong pond | 0-15 | 0.49 ± 0.02 | 4.67 ± 0.12 | 0.02 ± 0.001 | 34 ± 2 |
| | 15-30 | 0.51 ± 0.02 | 4.47 ± 0.12 | 0.02 ± 0.001 | 34 ± 2 |
| | 30-50 | 0.60 ± 0.04 | 4.54 ± 0.15 | 0.03 ± 0.001 | 54 ± 3 |
| | 50-100 | 0.64 ± 0.01 | 4.69 ± 0.13 | 0.03 ± 0.001 | 147 ± 6 |
| | 100-300 | 0.54 ± 0.03 | 5.95 ± 0.37 | 0.03 ± 0.001 | 231 ± 56 |
| Mean | | 0.56 ± 0.03 | 4.86 ± 0.28 | 0.03 ± 0.00 | 500 ± 53 |
| Kadutan pond | 0-15 | 0.35 ± 0.06 | 7.9 ± 0.84 | 0.03 ± 0.002 | 39 ± 3 |
| | 15-30 | 0.37 ± 0.03 | 7.05 ± 0.58 | 0.03 ± 0.002 | 38 ± 4 |
| | 30-50 | 0.46 ± 0.04 | 5.76 ± 0.70 | 0.03 ± 0.001 | 51 ± 3 |
| | 50-100 | 0.48 ± 0.03 | 5.43 ± 0.62 | 0.03 ± 0.002 | 128 ± 11 |
| | 100-300 | 0.58 ± 0.02 | 4.02 ± 0.20 | 0.02 ± 0.001 | 461 ± 21 |
| Mean | | 0.45 ± 0.04 | 6.05 ± 0.68 | 0.03 ± 0.00 | 717 ± 26 |
| Muara Berau pond | 0-15 | 0.45 ± 0.08 | 4.44 ± 0.26 | 0.02 ± 0.003 | 30 ± 5 |
| | 15-30 | 0.48 ± 0.02 | 4.96 ± 0.18 | 0.02 ± 0.001 | 36 ± 2 |
| | 30-50 | 0.50 ± 0.02 | 4.71 ± 0.15 | 0.02 ± 0.001 | 47 ± 2 |

| | | | | | |
|---|---|---|---|---|---|
| | 50-100 | 0.48 ± 0.02 | 4.93 ± 0.23 | 0.02 ± 0.002 | 119 ± 11 |
| | 100-300 | 0.58 ± 0.02 | 3.81 ± 0.16 | 0.02 ± 0.001 | 360 ± 44 |
| Mean | | 0.50 ± 0.02 | 4.57 ± 0.21 | 0.02 ± 0.00 | 592 ± 46 |
| Salette pond | 0-15 | 0.62 ± 0.05 | 6.01 ± 0.55 | 0.04 ± 0.002 | 54 ± 3 |
| | 15-30 | 0.63 ± 0.03 | 5.57 ± 0.29 | 0.04 ± 0.002 | 53 ± 3 |
| | 30-50 | 0.65 ± 0.03 | 6.89 ± 1.53 | 0.04 ± 0.007 | 86 ± 14 |
| | 50-100 | 0.67 ± 0.06 | 4.28 ± 0.19 | 0.03 ± 0.002 | 106 ± 14 |
| | 100-300 | 0.69 ± 0.05 | 5.01 ± 0.65 | 0.03 ± 0.003 | 75 ± 62 |
| Mean | | 0.65 ± 0.01 | 5.55 ± 0.44 | 0.04 ± 0.00 | 374 ± 80 |
| Sepatin pond | 0-15 | 0.43 ± 0.04 | 5.19 ± 0.34 | 0.02 ± 0.002 | 32 ± 3 |
| | 15-30 | 0.43 ± 0.06 | 6.10 ± 0.43 | 0.03 ± 0.002 | 38 ± 4 |
| | 30-50 | 0.50 ± 0.03 | 6.74 ± 0.94 | 0.03 ± 0.007 | 69 ± 13 |
| | 50-100 | 0.53 ± 0.06 | 5.09 ± 0.49 | 0.03 ± 0.002 | 131 ± 9 |
| | 100-300 | 0.48 ± 0.04 | 5.12 ± 0.28 | 0.02 ± 0.001 | 367 ± 83 |
| Mean | | 0.47 ± 0.02 | 5.65 ± 0.33 | 0.03 ± 0.00 | 637 ± 67 |
| Benati dalam pond | 0-15 | 0.43 ± 0.04 | 4.29 ± 0.14 | 0.02 ± 0.002 | 28 ± 3 |
| | 15-30 | 0.50 ± 0.05 | 4.40 ± 0.18 | 0.02 ± 0.002 | 33 ± 4 |
| | 30-50 | 0.55 ± 0.02 | 4.19 ± 0.07 | 0.02 ± 0.001 | 46 ± 3 |
| | 50-100 | 0.57 ± 0.04 | 4.21 ± 0.25 | 0.02 ± 0.002 | 115 ± 10 |
| | 100-300 | 0.59 ± 0.04 | 4.07 ± 0.53 | 0.02 ± 0.003 | 313 ± 94 |
| Mean | | 0.53 ± 0.03 | 4.23 ± 0.06 | 0.02 ± 0.00 | 536 ± 84 |
| Tanjung nipah pond | 0-15 | 0.76 ± 0.09 | 4.42 ± 0.11 | 0.03 ± 0.003 | 50 ± 4 |
| | 15-30 | 0.63 ± 0.03 | 4.95 ± 0.39 | 0.03 ± 0.002 | 46 ± 3 |
| | 30-50 | 0.55 ± 0.05 | 6.01 ± 0.64 | 0.03 ± 0.001 | 61 ± 4 |
| | 50-100 | 0.60 ± 0.02 | 5.99 ± 0.47 | 0.04 ± 0.003 | 130 ± 28 |
| | 100-300 | 0.81 ± 0.02 | 3.57 ± 0.42 | 0.03 ± 0.003 | 80 ± 47 |
| Mean | | 0.67 ± 0.05 | 4.99 ± 0.47 | 0.03 ± 0.00 | 367 ± 70 |
| Perangat pond | 0-15 | 0.43 ± 0.01 | 5.98 ± 0.56 | 0.03 ± 0.002 | 38 ± 4 |
| | 15-30 | 0.48 ± 0.05 | 6.44 ± 0.82 | 0.03 ± 0.002 | 43 ± 2 |
| | 30-50 | 0.45 ± 0.05 | 7.70 ± 0.73 | 0.03 ± 0.003 | 66 ± 5 |
| | 50-100 | 0.51 ± 0.05 | 6.63 ± 1.18 | 0.03 ± 0.003 | 158 ± 16 |
| | 100-300 | 0.51 ± 0.02 | 4.28 ± 0.29 | 0.02 ± 0.001 | 357 ± 50 |
| Mean | | 0.48 ± 0.02 | 6.20 ± 0.56 | 0.03 ± 0.00 | 663 ± 52 |

## References

Adame, M.F., Kauffman, J.B., Medina, I., Gamboa, J.N., Torres, O., Caamal, J.P., Herrera-silveira, J.A., 2013. Carbon stocks of tropical coastal wetlands within the karstic landscape of the Mexican Caribbean. PLoS One 8 (2). https://doi.org/10.1371/journal.pone.0056569.

Alongi, D.M., 2008. Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. Estuar. Coast. Shelf Sci. 76 (1), 1–13. https://doi.org/10.1016/j.ecss.2007.08.024.

Alongi, D.M., 2009. The Energetics of Mangrove Forests. Springer, Queensland, Australia.

Amira, S., 2008. Pendugaan Biomassa Jenis Rhizophora apiculata Bl. di Hutan Mangrove Batu Ampar Kabupaten Kubu Raya, Kalimantan Barat. Institut Pertanian Bogor.

Aslan, 2017. Novel uses of active and passive remotely sensed data for monitoring spatiotemporal dynamics of mangroves (Order No. 10276162). Available from ProQuest Dissertations & Theses Global. (1899598508). PhD dissertation. Indiana University. Retrieved from < http://proxyiub.uits.iu.edu/login?url=https://search-proquest-com.proxyiub.uits.iu.edu/docview/1899598508?accountid=11620 > .

Banerjee, K., Sengupta, K., Raha, A., Mitra, A., 2013. Salinity based allometric equations for biomass estimation of Sundarban mangroves. Biomass Bioenergy 56, 382–391. https://doi.org/10.1016/j.biombioe.2013.05.010.

Basuki, I., 2017. Carbon dynamics in response to land cover change in tropical peatlands, Kalimantan. PhD dissertation, Oregon State University, USA.

Batey, T., McKenzie, D.C., 2006. Soil compaction: Identification directly in the field. Soil Use Manage. 22 (2), 123–131. https://doi.org/10.1111/j.1475-2743.2006.00017.x.

Bhomia, R.K., Mackenzie, R.A., Murdiyarso, D., Sasmito, S.D., Purbopuspito, J., 2016. Impacts of land use on Indian mangrove forest carbon stocks: implications for conservation and management. Ecol. Appl. 26 (5), 1396–1408. https://doi.org/10.1890/15-2143.

Biswas, H., Mukhopadhyay, S.K., Sen, S., Jana, T.K., 2007. Spatial and temporal patterns of methane dynamics in the tropical mangrove dominated estuary, NE coast of Bay of Bengal, India. J. Mar. Syst. 68 (1–2), 55–64. https://doi.org/10.1016/j.jmarsys.2006.11.001.

Blasco, F., Saenger, P., Janodet, E., 1996. Mangroves as indicator of coastal change. Catena 27 (3), 167–178. https://doi.org/10.1016/0341-8162(96)00013-6.

Bosma, R., Sidik, A.S., Zwieten, P., Aditya, A., Visser, L., 2012. Challenges of a transition to a sustainably managed shrimp culture agro-ecosystem in the Mahakam delta, East Kalimantan, Indonesia. Wetlands Ecol. Manage. 20 (2), 89–99. https://doi.org/10.1007/s11273-011-9244-0.

Bourgeois, R., Gouyon, A., Jésus, F., Levang, P., Langeraar, W., Rahmadani, F., 2002. Socioeconomic and institutional analysis of. Mahakam Delta stakeholders.

Cahoon, D.R., Hensel, P., Rybczyk, J., McKee, K.L., Proffitt, C.E., Perez, B.C., 2003. Mass tree mortality leads to mangrove peat collapse at Bay Islands, Honduras after Hurricane Mitch. J. Ecol. 91 (6), 1093–1105. https://doi.org/10.1046/j.1365-2745.2003.00841.x.

Clough, B.F., Scott, K., 1989. Allometric relationships for estimating above-ground biomass in six mangrove species. For. Ecol. Manage. 27 (2), 117–127.

Dharmawan, I.W.S., Siregar, C.A., 2008. Soil carbon and carbon estimation of Avicennia marina (Forsk.) Vierh. Stand at Ciasem, Purwakarta. J. For. Res. 4, 1–21.

Dinas Kelautan dan Perikanan Kabupaten Kutai Kartanegara, 2016. Potensi dan Produksi Komoditi Perikanan Delta Mahakam Tahun 2016. Tenggarong, Kalimantan Timur.

Donato, D.C., Kauffman, J.B., Murdiyarso, D., Kurnianto, S., Stidham, M., Kanninen, M., 2011. Mangroves among the most carbon-rich forests in the tropics. Nat. Geosci. 4 (5), 293–297. https://doi.org/10.1038/ngeo1123.

Duke, N.C., Meynecke, J.-O., Dittmann, S., Ellison, A.M., Anger, K., Berger, U., Dahdouh-Guebas, F., 2007. A world without mangroves? Science 317 (5834), 41–42. https://doi.org/10.1002/9780470114735.hawley00624.

FAO, 2007. The world's mangroves 1980-2005. FAO Forestry Paper, vol. 153. https://doi.org/978-92-5-105856-5.

FAO, 2014. The state of world fisheries and aquaculture: Opportunities and challenges. Food and Agriculture Oraganization of the United Nations, vol. 2014. FAO, Rome, Italy. https://doi.org/92-5-105177-1.

Germer, S., Neill, C., Krusche, A.V., Elsenbeer, H., 2010. Influence of land-use change on near-surface hydrological processes: undisturbed forest to pasture. J. Hydrol. 380 (3–4), 473–480. https://doi.org/10.1016/j.jhydrol.2009.11.022.

Giesen, W., Wulffraat, S., Zieren, M., Scholten, L., 2007. Mangrove Guidebook for Southeast Asia. Mangrove guidebook for Southeast Asia, FAO Regional Office for Asia and the Pacific Retrieved from http://www.cabdirect.org/abstracts/20083307268.html.

Giri, C., Zhu, Z., Tieszen, L.L., Singh, A., Gillette, S., Kelmelis, J.A., 2008. Mangrove forest distributions and dynamics (1975–2005) of the tsunami-affected region of Asia. J. Biogeogr. 35 (3), 519–528. https://doi.org/10.1111/j.1365-2699.2007.01806.x.

Giri, C., Ochieng, E., Tieszen, L.L., Zhu, Z., Singh, A., Loveland, T., Duke, N., 2010. Status and distribution of mangrove forests of the world using earth observation satellite data. Glob. Ecol. Biogeogr. 20 (1), 154–159. https://doi.org/10.1111/j.1466-8238.2010.00584.x.

Henriksson, P.J.G., Rico, A., Zhang, W., Ahmad-Al-Nahid, S., Newton, R., Phan, L.T., Guinee, J.B., 2015. Comparison of asian aquaculture products by use of statistically supported life cycle assessment. Environ. Sci. Technol. 49 (24), 14176–14183. https://doi.org/10.1021/acs.est.5b04634.

Hooijer, A., Silvius, M., Wösten, H., Page, S., Hooijer, A., Silvius, M., Page, S., 2006. PEAT-CO2, Assessment of CO2 emissions from drained peatlands in SE Asia. Delft Hydraulics Rep. Q3943 (2006).

Hu, Z., Lee, J.W., Chandran, K., Kim, S., Khanal, S.K., 2012. Nitrous Oxide (N2O) Emission from aquaculture: a review. Environ. Sci. Technol. 46, 6470–6480. https://doi.org/10.4314/bajopas.v2i2.63717.

Ilman, M., Wiharyanto, D., Desyana, C., 2009. Kajian Dasar Budidaya Udang di Pesisir Utara. Kalimantan Timur.

Ilman, M., Wibisono, I.T.C., Suryadiputra, I.N.N., 2011. State of the Art Information on Mangrove Ecosystems in Indonesia. Wetlands International-Indonesia Programme, Bogor, Indonesia.

IPCC, 2014. Coastal Wetlands. In: Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., Troxler, T.G. (Eds.), 2013 Supplement to to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands. IPCC, Switzerland, pp. 1–55.

IPCC, 2006. 2006 IPCC Guidelines For National Greenhouse Gas Inventories.

Järviö, N., Henriksson, P.J.G., Guinée, J.B., 2017. Including GHG emissions from mangrove forests LULUC in LCA: a case study on shrimp farming in the Mekong Delta, Vietnam. Int. J. Life Cycle Assess. https://doi.org/10.1007/s11367-017-1323-x.

Jonell, M., Henriksson, P.J.G., 2015. Mangrove-shrimp farms in Vietnam-Comparing organic and conventional systems using life cycle assessment. Aquaculture 447, 66–75. https://doi.org/10.1016/j.aquaculture.2014.11.001.

Kangkuso, A., Jamili, J., Septiana, A., Raya, R., Sahidin, I., Rianse, U., Nadaoka, K., 2015. Allometric models and aboveground biomass of Lumnitzera racemosa Willd. forest in Rawa Aopa Watumohai National Park, Southeast Sulawesi, Indonesia. For. Sci. Technol., (July), 1–8. https://doi.org/10.1080/21580103.2015.1034191.

Kartanegara, Badan Pusat Statistik Kabupaten Kutai, 2010. Kutai Kartanegara dalam angka 2010 (Kutai Kartanegara in figures 2010). Tenggarong, Kalimantan Timur.

Kartanegara, Badan Pusat Statistik Kabupaten Kutai, 2013. Kutai Kartanegara dalam angka 2013 (Kutai Kartanegara in figures 2013). Tenggarong, Kalimantan Timur.

Kauffman, J.B., Donato, D.C., 2012. Protocols for the measurement, monitoring and reporting of structure, biomass and carbon stocks in mangrove forests (No. 86). Bogor, Indonesia.

Kauffman, J.B., Cole, T.G., 2010. Micronesian mangrove forest structure and tree responses to a severe typhoon. Wetlands 30 (6), 1077–1084. https://doi.org/10.1007/s13157-010-0114-y.

Kauffman, J.B., Cummings, D.L., Ward, D.E., 1998. Fire in the Brazilian Amazon 2. Biomass, nutrient pools and losses in cattle pastures. Oecologia 113, 415–427.

Kauffman, J.B., Trejo, H., Carmen, M., Garcia, J., Heider, C., Contreras, M., 2015. Carbon stocks of mangroves and losses arising from their conversion to cattle pastures in the Pantanos de Centla, Mexico. Wetlands Ecol. Manage., 23(3). https://doi.org/10.1007/s11273-015-9453-z.

Kauffman, J.B., Arifanti, V.B., Trejo, H., Jesús García, M. del C., Norfolk, J., Hadriyanto, D., Cifuentes-Jara, M., 2017. The jumbo carbon footprint of a shrimp: carbon losses from mangrove deforestation. Front. Ecol. Environ. https://doi.org/10.1002/fee.1482.

Kauffman, J.B., Heider, C., Norfolk, J., Payton, F., 2014. Carbon stocks of intact mangroves and carbon emissions arising from their conversion in the Dominican Republic. Ecol. Appl. 24 (3), 518–527. https://doi.org/10.1890/13-0640.1.

Komiyama, A., Poungparn, S., Kato, S., 2005. Common allometric equations for estimating the tree weight of mangroves. J. Tropical Ecol. 21 (4), 471–477. https://doi.org/10.1017/S0266467405002476.

Krauss, K.W., Cahoon, D.R., Allen, J.A., Ewel, K.C., Lynch, J.C., Cormier, N., 2010. Surface elevation change and susceptibility of different mangrove zones to sea-level rise on Pacific high islands of Micronesia. Ecosystems 13 (1), 129–143. https://doi.org/10.1007/s10021-009-9307-8.

Krauss, K.W., Mckee, K.L., Lovelock, C.E., Cahoon, D.R., Saintilan, N., Reef, R., Chen, L., 2014. Tansley review How mangrove forests adjust to rising sea level, 19–34.

Kusmana, C., Sabiham, S., Abe, K., Watanabe, H., 1992. An Estimation of above ground tree biomass of a mangrove forest in east sumatra, Indonesia. Tropics 1 (4), 243–257. https://doi.org/10.3759/tropics.1.243.

Lang'at, J.K.S., Kairo, J.G., Mencuccini, M., Bouillon, S., Skov, M.W., Waldron, S., Huxham, M., 2014. Rapid losses of surface elevation following tree girdling and cutting in tropical mangroves. PloS One, 9(9), 1–8. https://doi.org/10.1371/journal.pone.0107868.

Mitsch, W.J., Bernal, B., Nahlik, A.M., Mander, Ü., Zhang, L., Anderson, C.J., Brix, H., 2012. Wetlands, carbon, and climate change. Landscape Ecol. 28 (4), 583–597. https://doi.org/10.1007/s10980-012-9758-8.

Mitsch, W.J., Gosselink, J.G., 2007. Wetlands. John Wiley & Sons Inc, New Jersey, USA.

Murdiyarso, D., Purbopuspito, J., Kauffman, J.B., Warren, M.W., Sasmito, S.D., Donato, D. C., Kurnianto, S., 2015. The potential of Indonesian mangrove forests for global climate change mitigation. Nat. Clim. Change, (July), 8–11. https://doi.org/10.1038/nclimate2734.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Zhang, H., 2013. 2013: Anthropogenic and natural radiative forcing. In: Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, USA, pp. 659–740. https://doi.org/10.1017/ CBO9781107415324.018.

Nagelkerken, I., Blaber, S.J.M., Bouillon, S., Green, P., Haywood, M., Kirton, L.G., Somerfield, P.J., 2008. The habitat function of mangroves for terrestrial and marine fauna: a review. Aquat. Bot. 89 (2), 155–185. https://doi.org/10.1016/j.aquabot.2007.12.007.

Nijdam, D., Rood, T., Westhoek, H., 2012. The price of protein: review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes. Food Policy 37 (6), 760–770. https://doi.org/10.1016/j.foodpol.2012.08.002.

Noryadi, Bambang, I.G., Maidie, A., Suyatna, I., Sidik, A.S., Suripno, 2006. A study on pond productivity in Mahakam delta, East Kalimantan. FPIK/UNMUL, Samarinda.

Ong, J.E., Gong, W.K., Wong, C.H., 2004. Allometry and partitioning of the mangrove, *Rhizophora apiculata*. For. Ecol. Manage. 188 (1–3), 395–408. https://doi.org/10.1016/j.foreco.2003.08.002.

Pendleton, L., Donato, D.C., Murray, B.C., Crooks, S., Jenkins, W.A., Sifleet, S., Baldera, A., 2012. Estimating global "blue carbon" emissions from conversion and degradation of vegetated coastal ecosystems. PloS One 7 (9), e43542. https://doi.org/10.1371/journal.pone.0043542.

Poffenbarger, H.J., Needelman, B.A., Megonigal, J.P., 2011. Salinity influence on methane emissions from tidal marshes. Wetlands 31 (5), 831–842. https://doi.org/10.1007/s13157-011-0197-0.

Rahman, A.F., Dragoni, D., Didan, K., Barreto-Munoz, A., Hutabarat, J.A., 2013. Detecting large scale conversion of mangroves to aquaculture with change point and mixed-pixel analyses of high-fidelity MODIS data. Remote Sens. Environ. 130, 96–107. https://doi.org/10.1016/j.rse.2012.11.014.

Register, Federal, 2010. Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards. Environmental Protection Agency & Department of Transportation, Final Rule.

Rönnbäck, P., 1999. Analysis the ecological basis for economic value of seafood production supported by mangrove ecosystems. Ecol. Econ. 29, 235–252. https://doi.org/10.1016/S0921-8009(99)00016-6.

Sassi, M.G., Hoitink, A.J.F., Brye, B., Vermeulen, B., Deleersnijder, E., 2011. Tidal impact on the division of river discharge over distributary channels in the Mahakam Delta. Ocean Dyn. 61 (12), 2211–2228. https://doi.org/10.1007/s10236-011-0473-9.

Setiawan, Y., Bengen, D.G., Kusmana, C., Pertiwi, S., 2015. Estimasi Nilai Eksternalitas Konversi Hutan Mangrove Menjadi Pertambakan di Delta Mahakam Kabupaten Kutai Kartanegara. Jurnal Penelitian Hutan Tanaman 12 (3), 201–210.

Spalding, M., Kainuma, M., Collins, L., 2010. World Atlas of Mangroves. Taylor & Francis, New York, USA.

Storms, J.E.A., Hoogendoorn, R.M., Dam, R.A.C., Hoitink, A.J.F., Kroonenberg, S.B., 2005. Late-Holocene evolution of the Mahakam Delta, East Kalimantan, Indonesia. Sediment. Geol. 180 (3–4), 149–166. https://doi.org/10.1016/j.sedgeo.2005.08.003.

Tacon, A.G.J., 2002. Thematic Review of Feeds and Feed Management Practices in. Shrimp Aquaculture.

Towatana, P., Voradaj, C., Panapitukkul, N., 2002. Changes in soil properties of abandoned shrimp ponds in Southern Thailand. Environ. Monitor. Assess. 74 (1), 45–65. https://doi.org/10.1023/A:1013802704889.

Turner, R.E., 2004. Coastal wetland subsidence arising from local hydrologic manipulations. Estuaries 27 (2), 265–272.

Van Wagner, C.E., 1968. The line intersect method in forest fuel sampling. Forest Sci. 14, 20–26.

van Zwieten, P.A.M., Sidik, A.S., Noryadi, Suyatna, I., Abdunnur, 2006. Aquatic food production in the coastal zone: data-based perceptions on the trade-off between mariculture and fisheries production of the mahakam delta and estuary, East Kalimantan, Indonesia. In: Hoanh, C.T., Tuong, T.P., Gowing, J.W., Hardy, B. (Eds.), Environments and Livelihoods in Tropical Coastal Zones. CAB International, Oxon, UK, pp. 219–236.

Warren, M.W., Kauffman, J.B., Murdiyarso, D., Anshari, G., Hergoualc'h, K., Kurnianto, S., Iswandi, a., 2012. A cost-efficient method to assess carbon stocks in tropical peat soil. Biogeosci. Discuss., 9(6), 7049–7071. https://doi.org/10.5194/bg-9-4477-2012.

Werf, G.R. Van Der, Randerson, J.T., Giglio, L., Collatz, G.J., Mu, M., Kasibhatla, P.S., van Leeuwen, T.T., 2010. Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009). Atmosph. Chem. Phys. 10, 11707–11735. https://doi.org/10.5194/acp-10-11707-2010.